POWER CONSUMPTION TESTS
OF A
BASCULE BRIDGE

BY
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POWER CONSUMPTION TESTS OF A BASCULE BRIDGE

A THESIS

PRESENTED BY

ARMIN L. SCHREIBER AND STUART N. MILLER

TO THE

PRESIDENT AND FACULTY

OF

ARMOUR INSTITUTE OF TECHNOLOGY

FOR THE DEGREE OF

BACHELOR OF SCIENCE

IN

CIVIL ENGINEERING

MAY 31, 1917

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F O R E W O R D

Through the hearty co-operation of the Bureau of Engineering, Division of Bridges, of the City of Chicago, and the Faculty of the ARMOUR INSTITUTE OF TECHNOLOGY, tests on the operation of a modern bascule bridge, as outlined in the following paper, were made possible and carried to a successful conclusion.

The writers wish to express their sincerest thanks to Mr. John C. Bley and Mr. C. F. Harrington of the Division of Bridges for their untiring interest and practical help, and to Professor John C. Penn of the Armour Institute faculty for his valuable assistance and co-operation.

It is hoped that this will only mark the beginning of a series of tests, which in time will complete the solution of the problems involved, and which will help in the perfecting of numerous small details tending to bring about more efficient bridge operation.

A. L. Schreiber,

Stuart N. Miller.

May 1st, 1917

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POWER CONSUMPTION TESTS OF A BASCULE BRIDGE

INTRODUCTION

The universal use today of electric power for operating lift, draw and bascule bridges of all types has come about because of its unquestionable advantages over all other sources of power. These advantages are many, the principal one being the great speed at which a bridge of the modern type can be opened and closed.

The electric motor is the only machine that can be relied upon to accomplish this at any and all times, and under all conditions of weather. It has done away with many of the old objections to the use of steam power for this purpose. In place of the boiler room, coal bunkers, steam engines and other equipment necessary in such a plant, the modern operating mechanism consists only of two compact motors and simple trains of gears.

As yet the gasoline engine has not demonstrated its adaptability to the conditions that obtain. It is now used only in a few installations as an emergency source of power. The time required to operate a bridge leaf in this way, as observed in an actual case, is fully fifteen times

as great as that required with the regular electric installation.

The presence of an unfailing supply of current in all modern cities where movable bridges are constructed, makes the argument in favor of electric power particularly convincing.

The problem, therefore, has been to adapt the present theory of bridge design to the successful types of electric motors on the market and their controlling apparatus. The selection of the right size and type of motor to accelerate the bridge leaf and to keep it moving under unfavorable conditions at a uniform speed, has been a difficult problem on account of the uncertainty as to the conditions which prevail and also because of the lack of accurate data pertaining to bridge operation.

Various attempts have been made by engineers interested in this matter to discover the relations existing between the factors making up the problem. Due to many obvious difficulties, little accurate information has been available. The tests outlined in these pages were undertaken to clear up as many of these difficulties as possible.

The Division of Bridges, of the Bureau of Engi-

neering of the City of Chicago, during the year 1916 completed three bascule bridges of the latest "City" type, the counterweighted trunnion bascule bridge. These bridges are over the Chicago, river--one at Lake Street, another at Webster Avenue, and the third at Belmont Avenue. The bridge at Lake Street over the South Branch is two-leaf, double deck construction, accommodating street cars, general traffic and foot passengers on the lower deck, and the double track of the elevated railroad on the upper deck. The bridge at Webster Avenue over the North Branch is of two-leaf, single deck construction and carries only general traffic and foot passengers. The one over the North Branch at Belmont Avenue is almost the exact counterpart of the Webster Avenue bridge, the chief difference being that it carries two street car tracks.

The need of a series of tests upon one of these bridges was brought to the notice of the writers, and arrangements were made to carry them out under the direction of the Bridge Division.

After due consideration, the Webster Avenue bridge was chosen as the one on which to make these tests. The principal reason for this choice was the absence of

street car and elevated traffic over it. A further reason was that the exposed position of the bridge made the effect of wind action more pronounced and easier to measure.

The Webster Avenue bridge, in brief, consists of two exactly similar leaves operated independently and with no mechanical connection other than a center lock which is operated from the west side. The total length of the two spans, center to center of pinions, is 182 feet 9 inches,

and the total width is 66 feet 0 inches. A general idea of the bridge can be obtained from the accompanying photographs and a further description of the bridge will not be given as it does not directly concern the tests. A description of the operating mechanism is necessary, however, to explain the use of the testing apparatus.

Each leaf is raised and lowered by means of two similar 50 H.P., 600 volt, direct current, series wound motors of street car type, which operate through a train of gears onto racks on the main trusses centered around the

pinions. The motors and gears are situated on either side of the counterweight. Brake bands are placed on drums geared directly to the motors and are controlled, as are the motors, from the operating house which is adjacent to and above the counterweight pit. The motors are operated with a drum controller of the street car type.

POWER CONSUMPTION TESTS OF A BASCULE BRIDGE

OBJECTS OF TESTS

In studying the conditions and the desired results, six distinct problems presented themselves for solution, namely:

1. The relation of the power consumed at any instant to the angle of the leaf with the horizontal at that instant.

2. The relative power consumed by the two leaves under similar conditions.

3. The features of the parallel operation of the two motors on each leaf.

4. The effect of wind and rain upon the maximum power consumption.

5. The accuracy of the balance of each leaf.

6. The spacing of the resistance steps in the controllers.

POWER CONSUMPTION TESTS OF A BASCULE BRIDGE

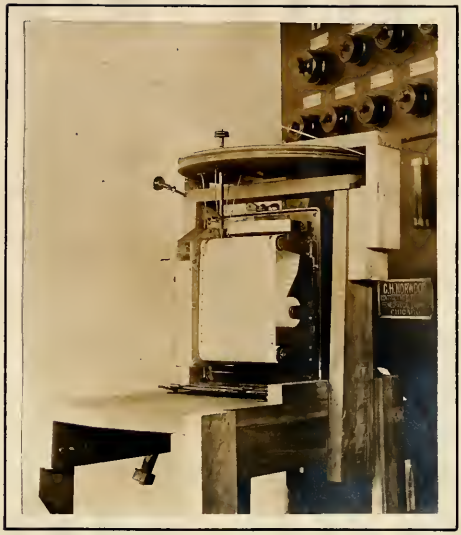
A P P A R A T U S

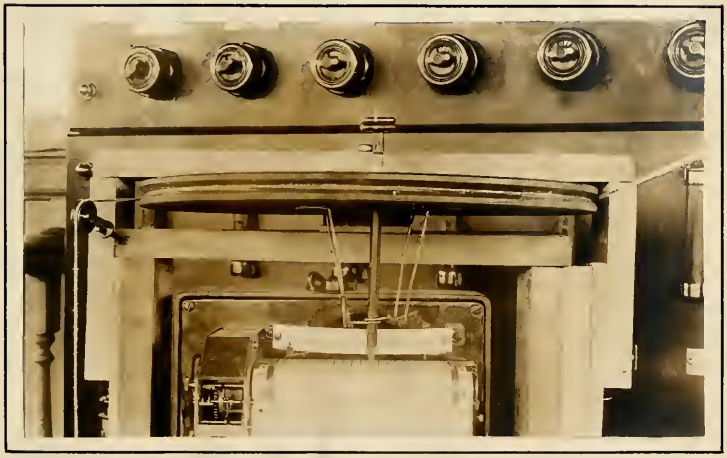
The following apparatus was used:

1. A recording wattmeter and auxiliary equipment.
2. A mechanical device to record the motion of the bridge leaf.
3. An anemometer to measure the velocity of the wind.

THE WATTMETER AND AUXILIARY EQUIPMENT.

The wattmeter used was a portable type, recording meter, manufactured by the Esterline Company of Indianapolis, Ind. It was designed to operate either on direct or alternating current at 5 amperes and 200 volts through each of its sets of coils. The drop over each current coil and its leads was given as 100 millivolts. The recording mechanism consisted of an inking needle swinging over a moving paper operated by clockwork. The paper was furnished in rolls to fit the meter and ruled with parallel lines so that it would register any power from zero to ten kilowatts.





The paper movement could be started and stopped at will by means of a catch.

In order to adapt the meter to the working conditions of the test, it was necessary to provide shunts of the proper size to reduce the current over the coils to less than 5 amperes each. It was found most convenient to connect each coil to a shunt in series with one motor. In this way, by disconnecting a lead to one coil, the share of the load taken by either motor could be determined.

Preliminary runs were made in the operation of the bridge and the probable maximum current at any time determined from the readings of the regular ammeter in the operating house, which was found to be 150 amperes. Consequently, two 75 ampere, 100 millivolt shunts were provided, and one was placed permanently behind the switchboard in the line to the north motor, and the other similarly in the line to the south motor. If it had not been desired to determine the load on each motor, only one 150-ampere shunt would have been placed in the main line. The meter was calibrated with these shunts before and after installation(p. 16).

The next problem was to reduce the voltage from 580 volts down to 200 volts, the allowed voltage over the voltage coils. This was done by placing a resistance in

series with each coil. The resistance of the coils being known, these external resistances were computed from the formula:

$$R = \frac{580 - 200}{200} Rc$$

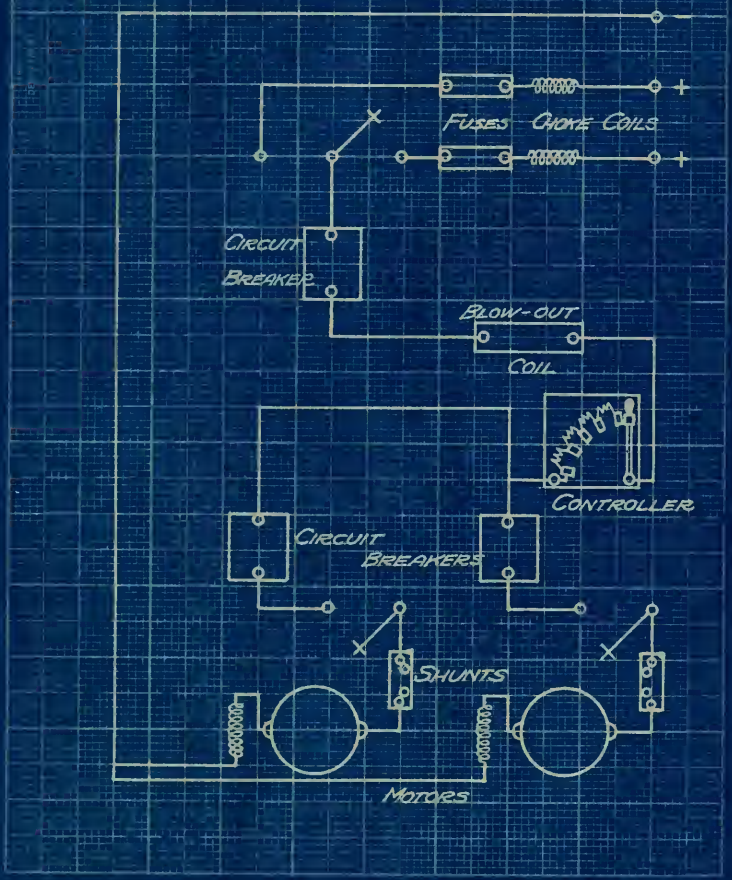
where R equals external resistance in ohms and Rc equals coil resistance in ohms. Accordingly when the meter was connected to the shunts and under the acting voltage, itwas ready at any time to record the power taken by the motors.

A calibration curve, curve "A" (cf. page 36), was prepared from the results of the meter calibration. The abscissae are the recorded power as given by the meter needle; the ordinates are the true power, or the product of the current through the shunts, the voltage over the leads, and the ratio $\frac{580}{200}$.

APPARATUS FOR RECORDING THE ANGULAR POSITION OF BRIDGE LEAF.

The problem involved here was to transfer the movement of the leaf in some accurate manner into the operating house and onto the moving paper which, at the same time, was receiving the record of the power, which has already been described. Of various methods considered, the following was decided upon.

Diagram of Motor Circuits Showing Parallel Connection & Control.



A braided steel picture wire was wound around that portion of the main trunnion protruding from the bearing on the end nearest the operating house; one end was fastened securely and the other led off as shown in the following picture.

This wire was then led up into the operating house by means of two iron pulleys and there hung over a large wooden pulley, bracketed to the wall and weighted so

as to be under a constant tension of ten pounds. From another pulley on the same shaft and fastened securely to the first, a wire was stretched across the room and wound around a large grooved disc, placed horizontally and directly over the wattmeter and counterweighted. The meter and disc were arranged on the stand provided for them, as the photograph on page No. 13 shows. A pencil was dropped through a closely fitted hole in the disc, so that, when the disc revolved, the pencil described an arc on the paper of the meter.

The radius of the arc described by this pencil was made the same as that described by the meter needle. However, the center of this arc was placed 3/8" beyond that of the needle to avoid any interference between the two.

By this arrangement, when any movement of the leaf occurred, the wire unwound from the trunnion and in so doing turned the disc through an angle proportional to the angular position of the leaf.

In order to find the instantaneous power corresponding to any angle of the leaf, it was necessary to move the leaf-angle curve a distance of 3/8 of an inch to the left, and read the corresponding ordinates of the two curves.

In drawing up the final curves, this was done and the whole transformed into rectangular co-ordinates with time as abscissae and leaf angle and power as ordinates.

The diameters of the pulleys were determined as follows:

The diameter of the trunnion equals 16.50 inches. Assuming that the leaf turned through 80°, the linear motion of the wire was:-

$$16.50 \times 3.142 \times 80 \div 360 = 11.51 \text{ inches}$$

This motion was communicated directly to the first pulley in the operating house, the diameter of which was made 6 inches. The diameter of the pulley connected to it was made 3-3/4 inches. Consequently, the linear motion of the wire leading from this second pulley was reduced from 11.51 inches to:-

$$11.51 \times 3\text{-}3/4 \div 6 = 7.20 \text{ inches}$$

It was found that the wattmeter needle had a swing of 60° over the full width of the paper and a radius of 4-7/16 inches. The movement of the needle point, therefore, for full scale deflection was:-

$$4\text{-}7/16 \times 2 \times 3.142 \times 60 \div 360 = 4.64 \text{ in.}$$

Therefore the radius of the disc necessary to reduce the

motion from 7.20 inches down to 4.64 inches was:-

$$7.20 \times 4\text{-}7/16 \div 4.64 = 6.875 \text{ inches}$$

or a diameter of disc of 13.75 inches.

These diameters were provided.

ANEMOMETER AND DETERMINATION OF TORQUE DUE TO WIND PRESSURE.

The anemometer used was of the vertical plane, revolving vane type. It was calibrated by moving it through still air, for definite times over a definite distance, from which a curve was obtained showing the actual velocity plotted against the recorded velocity.

In finding the means of determining the wind pressure upon the bridge leaf, the experiments of G. Eiffel in his book, "The Resistance of the Air and Aviation," were taken as the most reliable standard. Eiffel gives the formula:-

$$P = .0033\ SV^2 ,$$

where P equals total normal pressure in pounds, S equals area of surface in square feet, and V equals velocity of wind in m.p.h. The constant .0033 is his experimental constant.

A curve was obtained from the same data showing the distance of the center of pressure of the wind on a sur-

face plotted against the angle of the surface with the horizontal. Values of this distance in terms of the length of the bridge leaf, and values of S in the preceding formula were inserted in a new formula:-

$$M = pV^2$$

where M equals overturning moment in foot pounds, p is a constant determined from combining .0033S and the distances of the center of pressure as shown above, and V equals the velocity of the wind in feet per second.

Curve "B", page 37, gives values of V^2 and curve "C", page 38, gives values of p in this formula for all angles of the leaf with the horizontal. Thus the overturning moment of the wind at any angle of the leaf can be computed and then plotted along with the time--angle curve, or with the time--power curve.

POWER CONSUMPTION TESTS OF A BASCULE BRIDGE

R E S U L T S

The results obtained from the tests are in general purely relative ones. However, they show a high degree of accuracy in many details, since it was more the nature of the problem than the use of the apparatus that made them relative.

An excellent check was had on both the power curves and the angle curves. The power recorded at definite points was compared with that indicated by the reading of the ammeter in the operating house multiplied by the voltage, and found to average 96.4 per cent of that given by the operating house instruments. Much of this error was probably in the station ammeter itself. The angle curves checked closely with the angles shown on the indicating arc and were corrected, on transferring them to rectangular co-ordinates, to the exact values given by the indicating arc.

The greatest cause of error was in the lag of the wattmeter needle when indicating very low values. As this point was always passed when the first point on the control-

ler was reached, the error did not affect the results.

The results of the various parts of the tests are discussed in the following paragraphs.

1. The relation of the power consumed at any instant to the angle of the leaf with the horizontal at that instant.

Curves IA east leaf (page 39) and IB west leaf (page 40) show the relation clearly. These curves have had the proper calibration applied, as referred to under "Apparatus," and are in rectangular co-ordinates to facilitate their interpretation.

Referring to curve IA and reading forward from the lower left hand corner, it is seen that the power curve jumps from 0 to 36 kilowatts in three seconds and to 41 kilowatts in four seconds; gradually drops to 35 kilowatts in fifteen seconds; increases to 38.5 in thirty-one seconds, from which it drops abruptly to zero. The angle curve for the same period shows that the bridge does not start to rise until fully two seconds after the power is applied. After six seconds, the angle curve has assumed a uniform slope and continues at this slope until thirty-one seconds, when it begins to flatten out as the power is shut off.

This means that the leaf is maintained at a constant velocity throughout almost the entire run.

Between 32 and 38 seconds, the leaf is at rest, after which the power is applied and the leaf lowered. The power rises rapidly to 35 K.W. at 44 seconds and then falls gradually to 26 K.W. at 52 seconds, where it drops instantly to zero. The angle curve assumes a constant downward slope at 41 seconds, or three seconds after the power is applied and continues with this slope until 55 seconds, or three seconds after the power is cut off. From that point it gradually flattens out and reaches zero at 1 minute 18 seconds, which is the duration of the lift. The small jumps in the power curve are the power required to bring the leaf down the last three degrees.

Referring to this and other curves, the relation between the power and the angle of the leaf is found to be practically the same for all of them. In raising the leaf the power jumps to about 40 K.W. and remains nearly constant at this amount until shut off when the leaf is raised an average of 68°. In lowering the leaf, the power jumps to about 30 K.W. and then gradually drops to 25 K.W. when it is shut off. This cut-off point occurs generally at an

angle of 35 degrees with the horizontal.

One of the most notable properties of the angle curve is that the angular velocity of the leaf can be obtained from it. This is done by taking the difference between the two ordinates, betwen which the velocity is desired, and dividing by the elapse of time between them.

2. The relative power consumed by the two leaves under similar conditions.

To get definite results on this relation was very difficult because the results are easily hidden by the wind effect. Although at a glance over a number of curves, the total power consumed for either leaf averages quite well, the details vary in so many ways that no definite conclusion can be drawn from them. Only one lift on each leaf was obtained with the wind velocity down to zero, (see curves IIA and IIB on page 41). These curves show that the west leaf required 111.5 per cent of the total power required by the east leaf in raising, and at the same time, the east leaf required 108.5 per cent of the power used by the west leaf in lowering. The total power consumed in raising and lowering the east leaf was 95.3 per cent of the total power consumed in raising and lowering the west leaf.

This means, if this run is a characteristic one, that the east leaf operates more efficiently.

However, the starting torque of the east leaf is greater than that of the west leaf to the extent that it requires three kilowatts more power to overcome it. This determination was obtained from an average of seven runs on each leaf.

The time required to raise the east leaf, when no wind was blowing as seen in curves IIA and IIB, is 88 per cent of that required to raise the west leaf. The average time required to raise the east leaf, as shown by comparing ten runs, is 82 per cent of that required to raise the west leaf. This decrease in ratio is probably due to the wind.

3. The features of the parallel operation of the two motors on each leaf.

This part of the test was of particular interest because there existed no information in regard to the way the motors behaved under parallel operation. Although many other movable bridges in Chicago are operated with series-connected motors, on this bridge and a few others they are connected in parallel, as shown in the wiring diagram on page 16, because it was hoped that this connection would

give more satisfactory results. The matter of series or parallel connections has been a bone of contention among designers of bridge machinery for a long time, and it was hoped that this test would prove that the motors operated efficiently under parallel control.

The results show clearly and conclusively that such is the case. Curves IIIA west leaf and IIIB east leaf on pages 42 and 43, show the action of the motors. The results on either leaf are practically the same.

The upper part of curve IIIA was obtained as follows: The wattmeter was connected to record the total power until thirteen seconds, when one of the leads to the south motor was disconnected and the north motor allowed to record alone. At 17 seconds the south motor was again connected and the north motor immediately disconnected. At 21 seconds the north motor was again connected and both allowed to record until the power was shut off. On the downward movement the same scheme was followed.

The middle curve was obtained by making a complete run with only the north motor connected to the meter and the lower curve by making a complete run with only the south motor connected.

The two lower curves, in order to prove that the motors take the same load, should enclose equal areas. Although the runs for these curves were two minutes apart and did not represent exactly identical conditions, the curve areas are almost exactly equal. Since the runs were made as nearly alike as possible, the conclusion that the two motors are taking the same power is justified. All doubt is removed on examining the upper curve. There it is seen that the sections of the curve showing the north and south motors alone are exact continuations of each other.

Curve IIIB shows the same relations existing on the east leaf.

These tests, therefore, show conclusively that the parallel connection of the motors on the Webster Avenue bridge gives very efficient and successful operation.

4. The effect of the wind and rain on the maximum power consumption.

On every power curve obtained during the tests, the effect of wind pressure can be seen. As it so happened, the wind blew from the west on every day on which the bridge was operated. This made it impossible to test each leaf under wind pressures constant both in volume and

direction.

Furthermore, as the wind velocity never exceeded twelve miles per hour when the testing apparatus was ready, the very high pressures which the leaf is undoubtedly subjected to at times, could not be obtained very clearly. Curves IVA and IVB, page 44, show the effect of a west wind upon both leaves of the bridge. The wind had a velocity of 10.0 miles per hour. The total power required to raise the west leaf against the wind was 123 per cent of that required to raise the east leaf going with the wind. The total power required to lower the east leaf against the wind was fully 176 per cent of that required to move the west leaf with the wind.

Curve IVA shows the power increasing as the angle of the leaf increases, and curve IVB shows the power decreasing at the same time. This would indicate that, as the leaf swings up into the wind, the normal component of the wind pressure increases. This conclusion would naturally be inferred.

On curve IVC, page 45, it has been attempted to show the relation of the power consumed at any instant to the overturning moment due to the wind. The curve show-

ing the overturning moment was obtained from curves "B" and "C", pages 37 and 38, as follows:

First, the wind velocity of 20.5 feet per second, given by the anemometer, was entered in curve "B" and a value of V^2 of 150 obtained. Then the values of constant "p" were taken from curve "C" for every ten degrees of lift. The quantity pV^2 was next computed for each ten degree interval and laid off as ordinates through the points on the angle curve corresponding to these ten degree intervals. A curve was then drawn through these points. This curve shows a maximum overturning moment of 145,000 foot pounds, at 40 degrees for a wind velocity of 12.2 miles per hour, or the equivalent of a force of 1,590 pounds acting normal to the leaf on the off-shore end.

The overturning moment curve and the power curve do not show the relations which they should theoretically, throughout their length. The wind pressure being only a small per cent of all the forces tending to retard the leaf, this relation is consequently greatly obscured.

The data collected from all the curves in regard to wind action have shown the writers that attempts to measure the effects of the wind give only vague results where

actual values are considered. General effects are shown very well.

The effect of rain was found to be almost inappreciable. Only one run was obtained with the leaf covered with water. No apparent increase in power was to be noticed.

5. The accuracy of the balance of each leaf.

In designing and constructing the counterweight of each leaf, the attempt was made to give it such a weight that a current of from ten to twenty amperes more would be required to raise the leaf than to lower it. The results of the test show that this difference was not obtained. From an average of seven runs on the west leaf, the difference was found to be 26.7 amperes, and from an average of seven runs on the east leaf the difference was found to be 28.1 amperes, or nearly twice the average amount desired. An examination of any number of power curves will show that difference could have been decreased a great deal by increasing the counterweight, and there would still have been enough excess weight with the leaf closed for a large safety factor.

6. The spacing of the resistance steps in the con-

trollers.

Along with the other tests, it was hoped that some idea could be formed regarding the way the current was admitted to the motors and how this was controlled, especially at the moment of starting. Accordingly, the leaves were raised by throwing out the resistances very slowly, thereby giving curves which showed the current jumps distinctly. Curves VIA and VIB, page 46, give these steps.

On the controller on the west leaf on a high run of 39 amperes, the first point gave approximately 6 amps, the second 24 amps, the third 5 amps, the fourth 3 amps, and the fifth about 1 amp.

This shows that the second point cut out is much too large, and that especially the third and the fourth and also the fifth are too small. The first, however, should be rather low and is, therefore, about correct.

C O N C L U S I O N

In conclusion the writers wish to say that the power consumption tests brought results above their expectation. The difficulties that arose, although few in number, required a careful study of many details in order to solve them and to produce results in a form both simple and accurate.

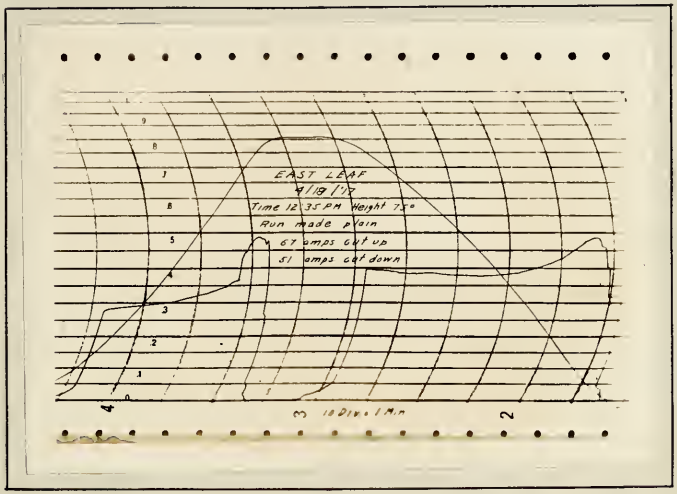
It has been demonstrated that the various objects sought in regard to bridge operation, can be brought out in the simple way described in this paper, thus making it possible to perform tests of this kind on any electrically operated bridge. Any individual bridge will present problems of its own, due to special factors entering into its construction, which may necessitate changes and elaborations of the testing apparatus. However, if the proper care is exercised in making and recording the actual tests, the methods described in this paper will undoubtedly produce satisfactory results and ultimately solve the problems connected with the operation of electrically controlled bridges.

It is hoped that the results of this investigation may contribute their quota to the solution of the problems of bridge operation, and that they may be of value in the future in the designing of bascule bridges of all types.

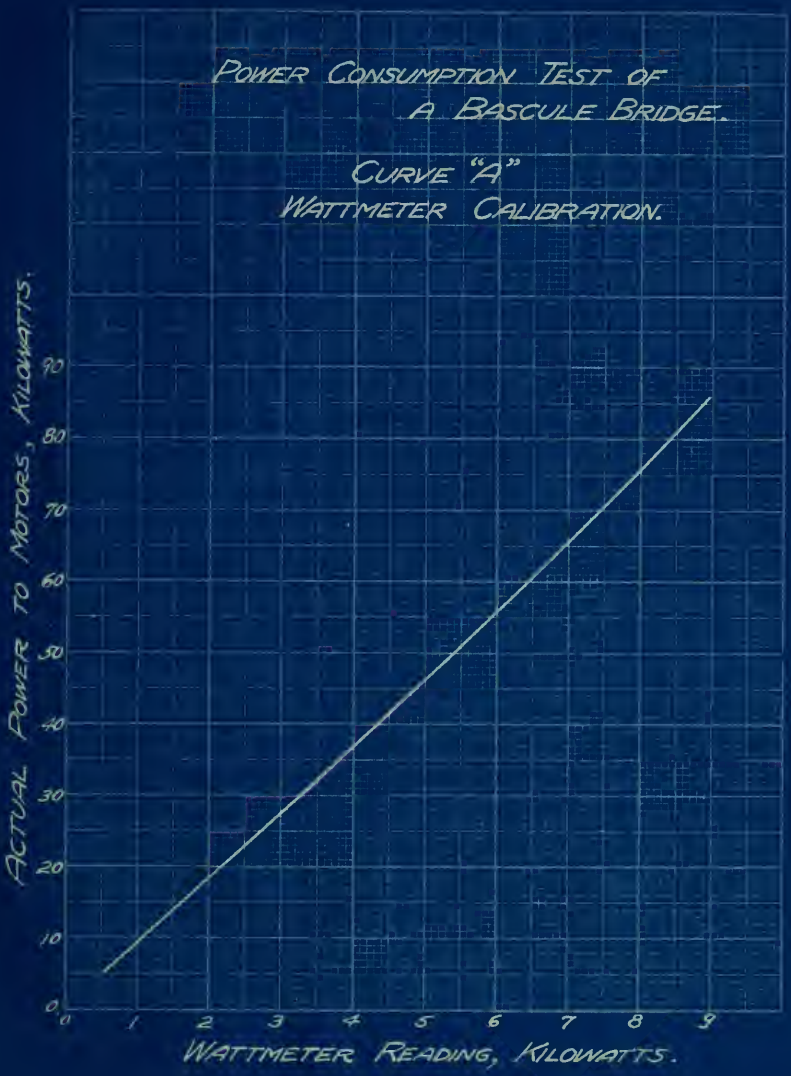
POWER CONSUMPTION TESTS OF A BASCULE BRIDGE

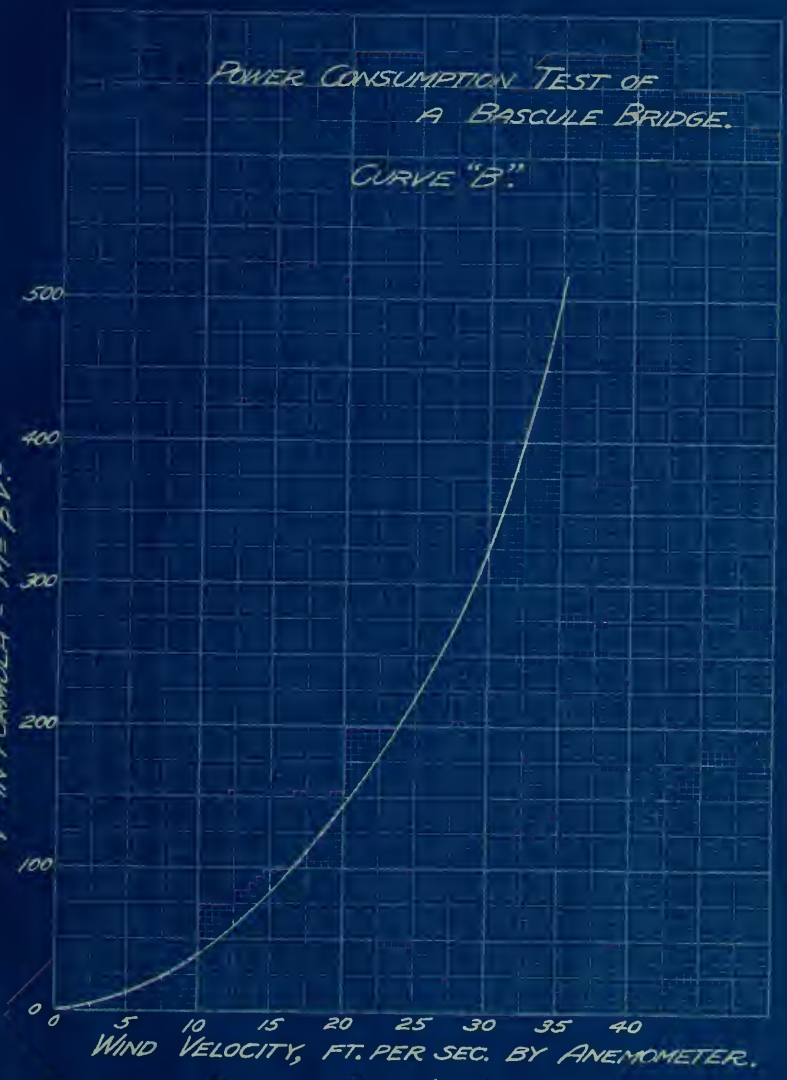
C U R V E S

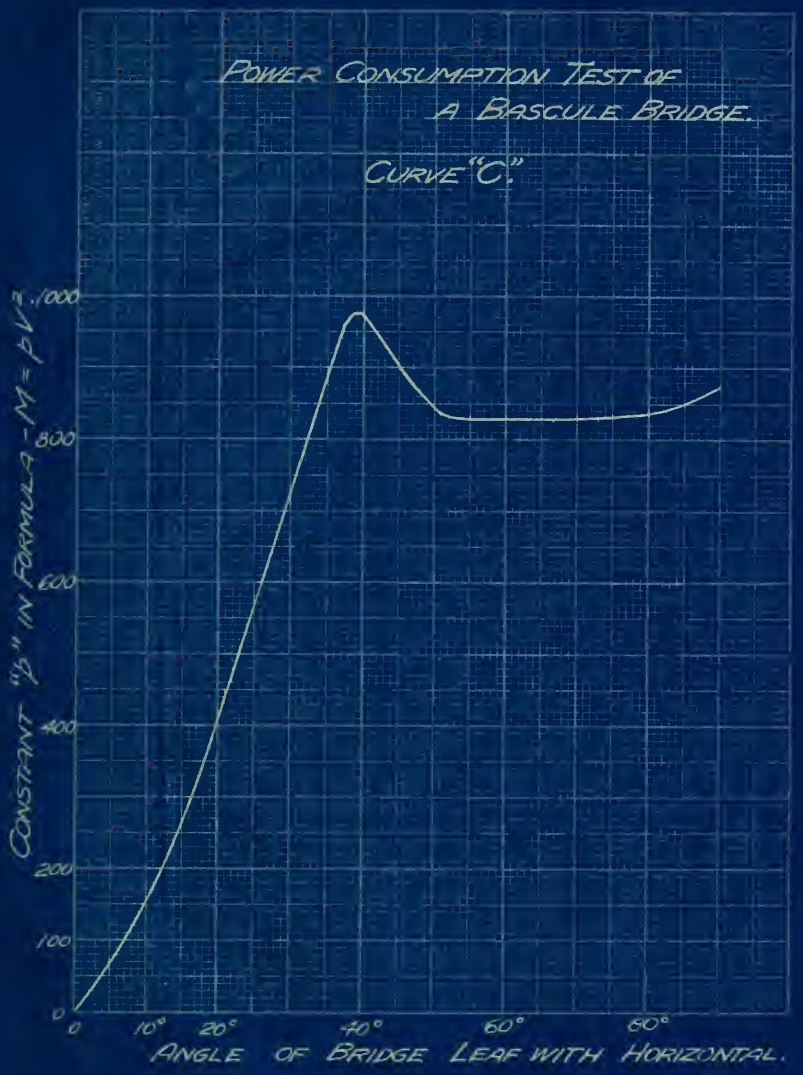
Below is a print of a typical curve as recorded by the instruments.

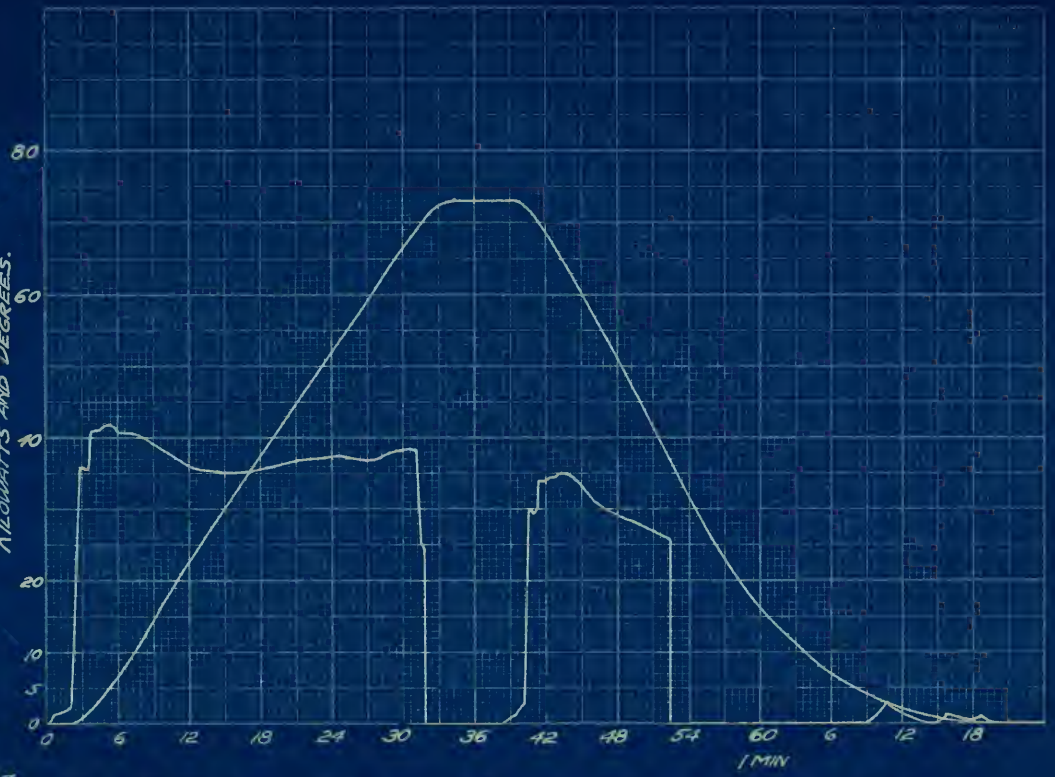


Following are prints of the transformed curves.


Power Consumption Test of
A Bascule Bridge.
Curve "A"
Wattmeter Calibration.
Actual Power to Motors, Kilowatts.
0
10
20
30
40
50
60
70
80
90
0
1
2
3
4
5
6
7
8
9
Wattmeter Reading, Kilowatts.

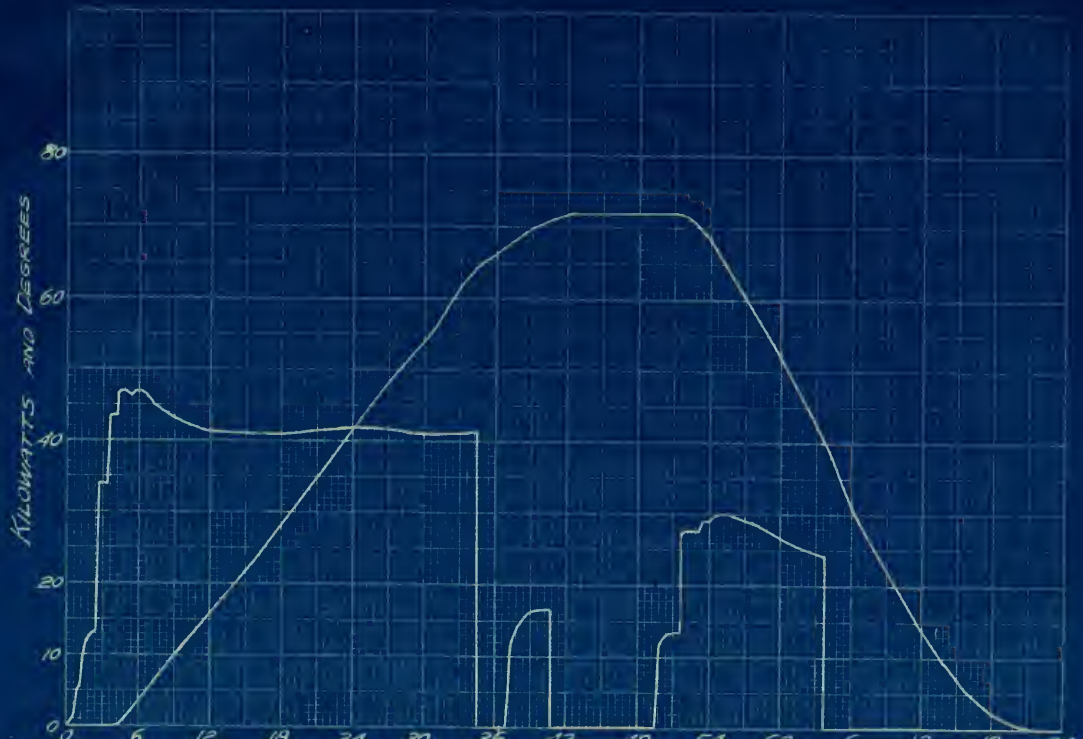

POWER CONSUMPTION TEST OF
A BASCULE BRIDGE.
CURVE "B".
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
V² IN FORMULA - M = A V²
WIND VELOCITY, FT. PER SEC. BY ANEMOMETER.


POWER CONSUMPTION TEST OF
A BASCULE BRIDGE.
CURVE "C."
CONSTANT "p" IN FORMULA - M = pV²
1000
800
600
400
200
100
0
0
10°
20°
40°
60°
80°
ANGLE OF BRIDGE LEAF WITH HORIZONTAL.



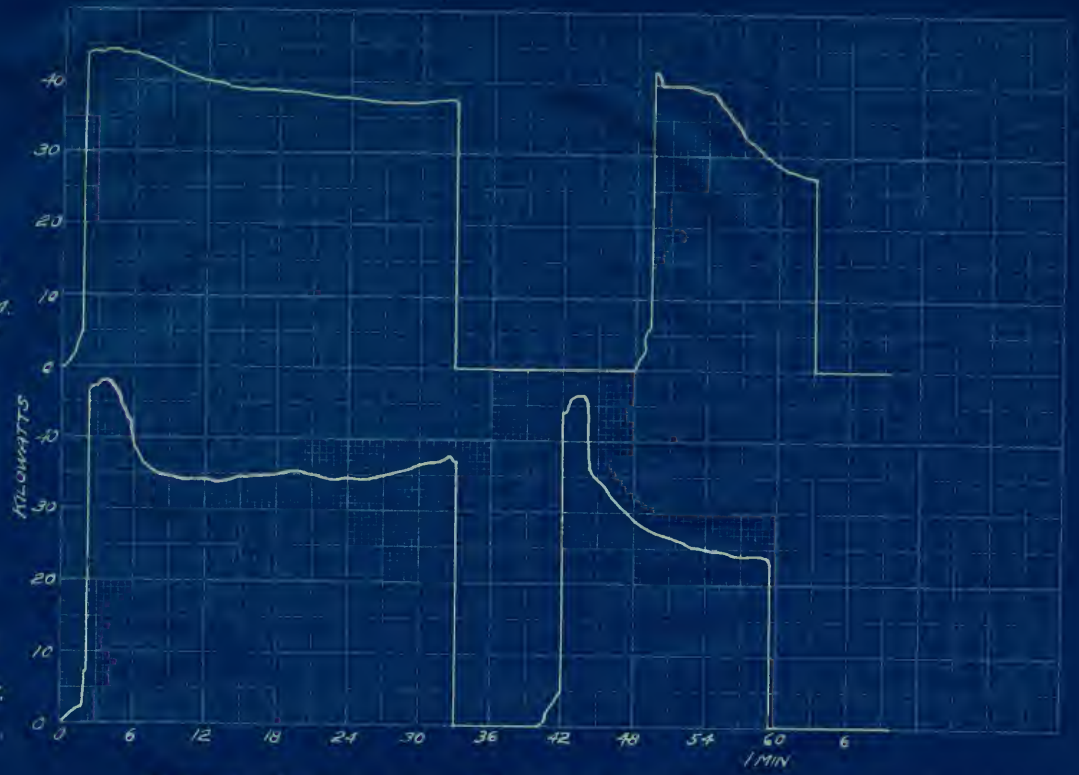
4/7/17
3:16 P.M.
EAST.

IA. CURVES SHOWING RELATION BETWEEN POWER AND ANGLE OF LEAF.

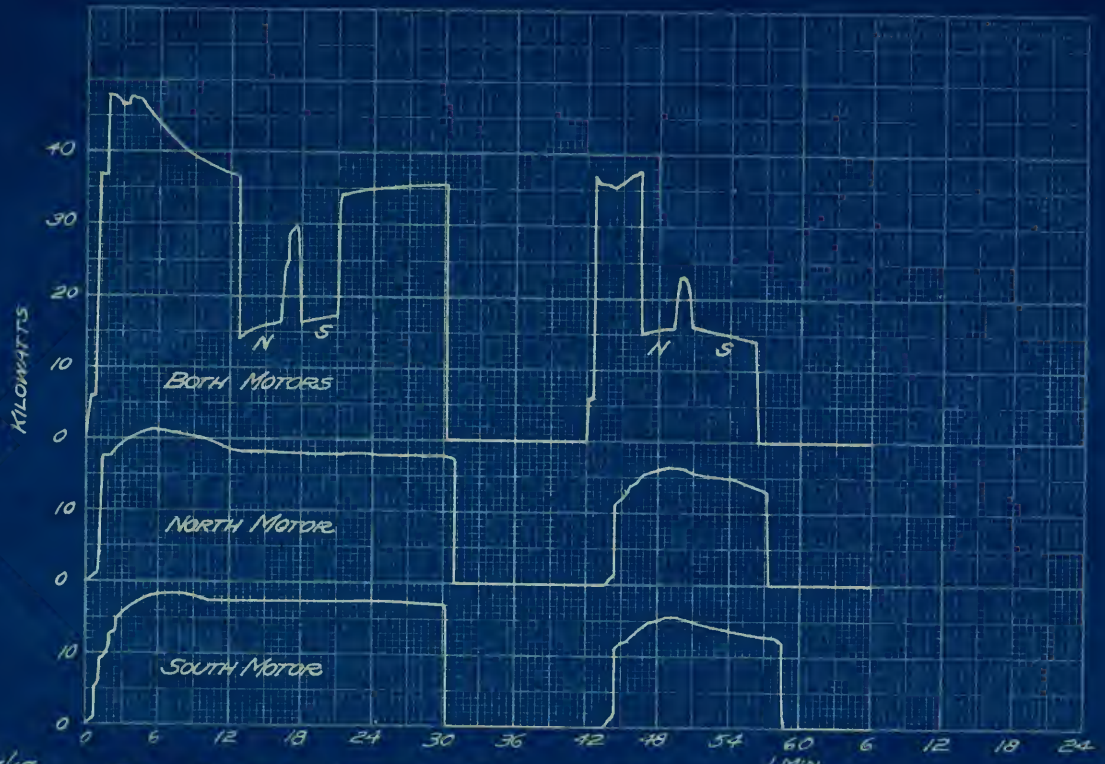


3/28/17
1:30 P.M.
WEST

-13- CURVES SHOWING RELATION BETWEEN POWER AND ANGLE OF LEAF.

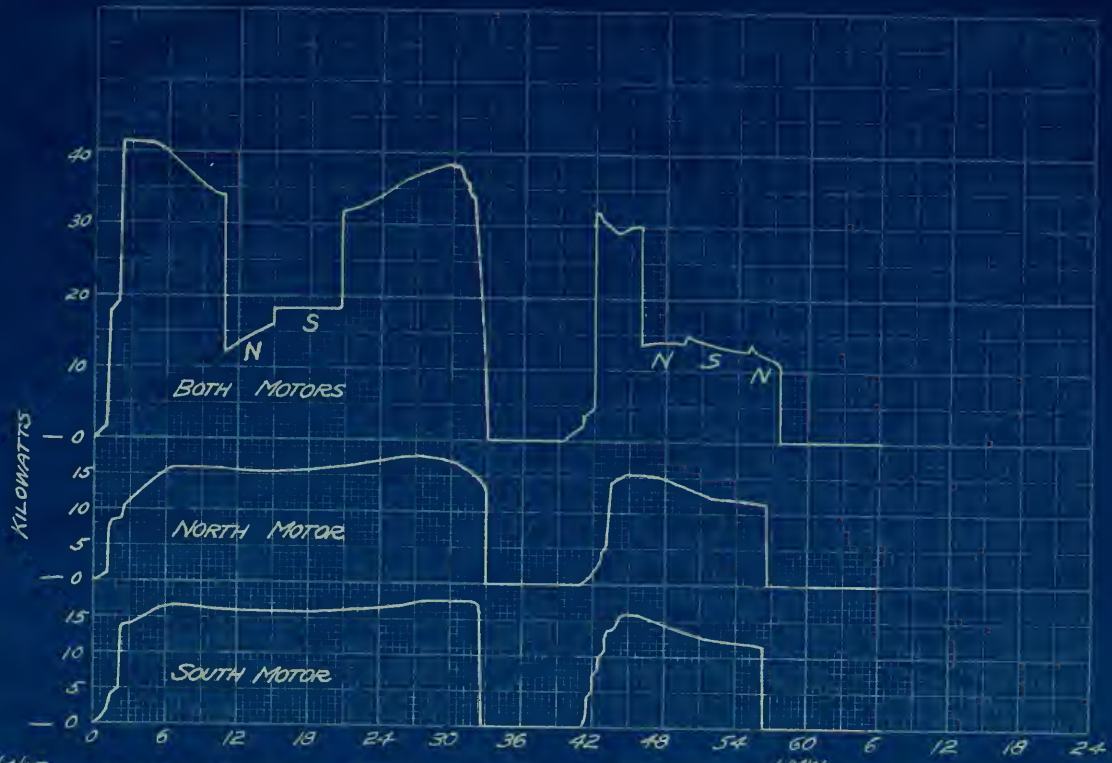


CURVES SHOWING THE RELATIVE POWER CONSUMED BY THE TWO LEAVES.



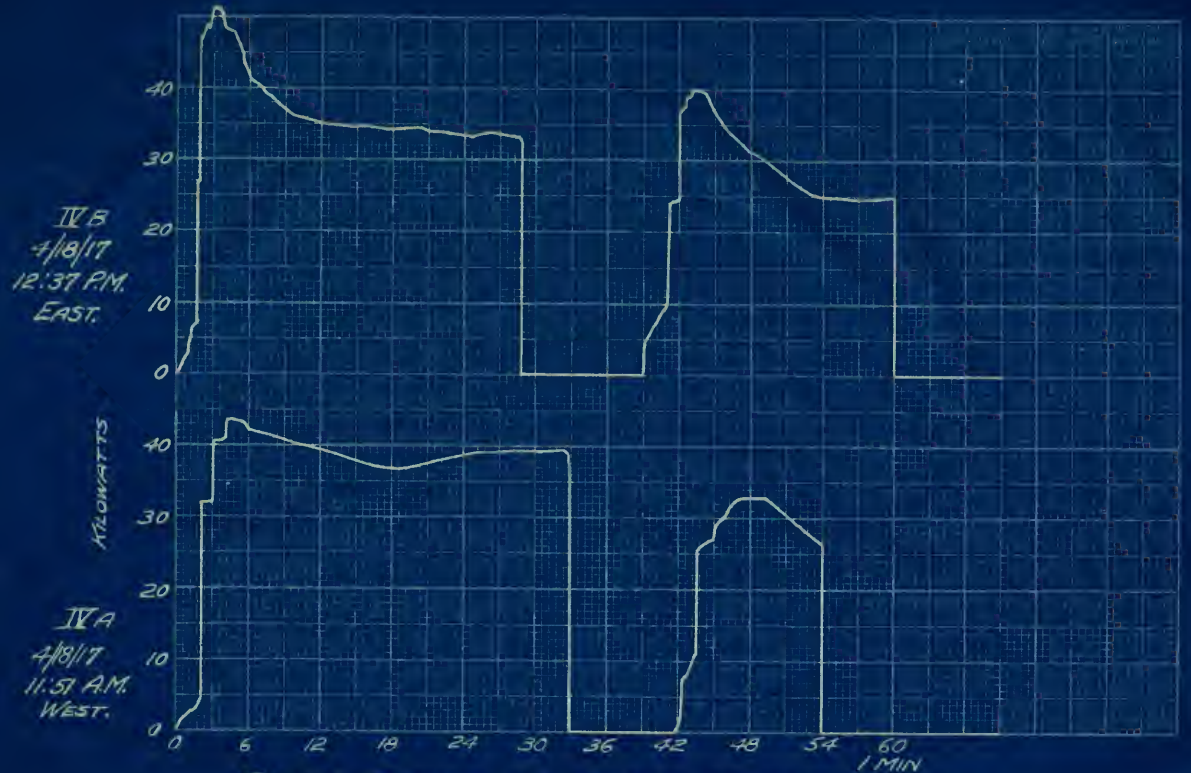
4/4/17
1:37 P.M.
WEST

III A CURVES SHOWING PARALLEL OPERATION OF MOTORS.

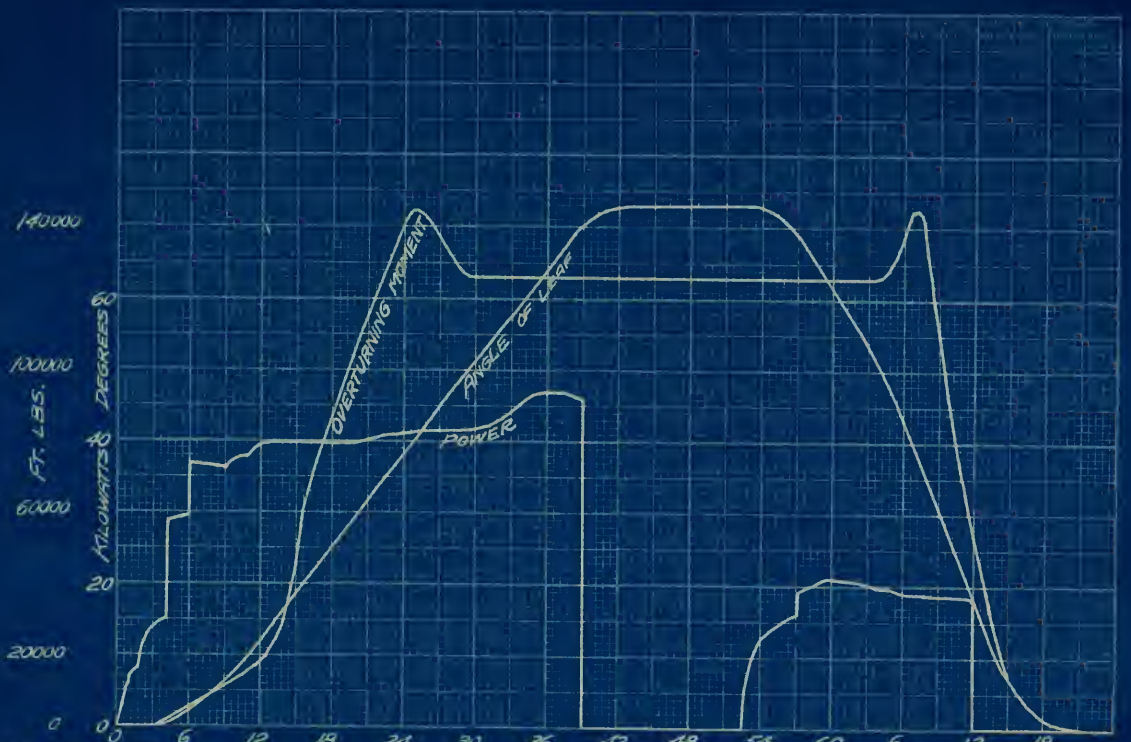


4/4/17
2.35 P.M
EAST.

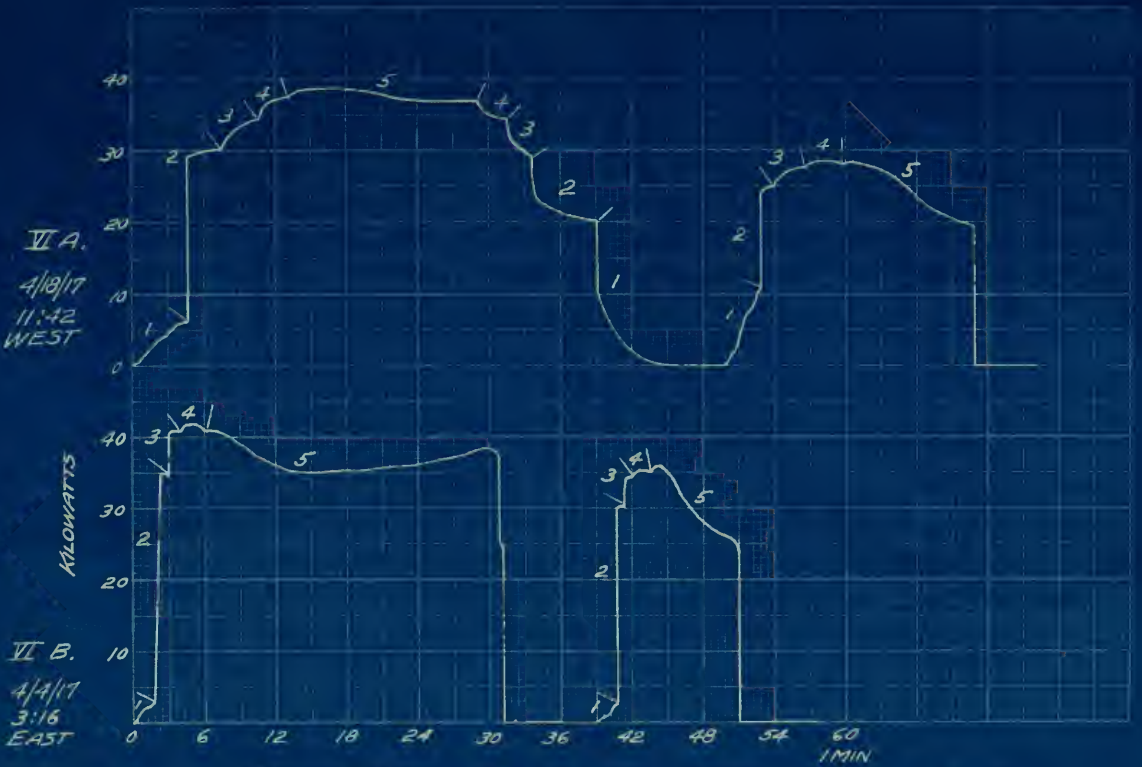
III B. CURVES SHOWING PARALLEL OPERATION OF MOTORS.



CURVES SHOWING THE EFFECT OF WIND PRESSURE.
V = 10.0 M.P.H.



IV C. CURVES SHOWING THE EFFECT OF WIND PRESSURE.
V = 12. M.P.H.



CURVES SHOWING RESISTANCE STEPS IN CONTROLLERS.